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Joseph Y. Halpern	
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13. SUPPLEMENTARY NOTES

14. ABSTRACT

In decision theory, it is typically assumed that a decision maker knows the state space, the outcome space, and the set of feasible acts. But this is far from clear in practice. In a complex decision problem, agents may be unaware of many relevant features, and thus unaware of possible states, outcomes, and feasible acts. This project has investigated how to proceed when these assumptions

15. SUBJECT TERMS

learning, awareness, decision theory, game theory, MDPs

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a. REPORT	b. ABSTRACT	c. THIS PAGE			Joseph Halpern
UU	UU	UU	UU		19b. TELEPHONE NUMBER
					607-255-9562

Agency Code:

Proposal Number: 64452NS   **Agreement Number: W911NF-14-1-0017**
INVESTIGATOR(S):

    Name: Joseph Halpern
    Email: halpern@cs.cornell.edu
    Phone Number: 6072559562
    Principal: Y

Organization: **Cornell University**
Address: Office of Sponsored Programs, Ithaca, NY 148502820
Country: USA
DUNS Number: 872612445   EIN: 150532082
Report Date: 17-Mar-2017   Date Received: 15-Aug-2018
Final Report for Period Beginning 18-Dec-2013 and Ending 17-Dec-2016
Title: Learning, Awareness, Optimism, and Confidence
Begin Performance Period: 18-Dec-2013   **End Performance Period:** 17-Dec-2016
Report Term: 0-Other
Submitted By: Joseph Halpern   Email: halpern@cs.cornell.edu
                                                   Phone: (607) 255-9562
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STEM Degrees: 0   **STEM Participants:** 3

Major Goals: The goal of this project is to investigate operations on causal models
that will be critical making best use of causal information. The
initial focus will be on two operations: combining models and
abstracting models.

With regard to combining models, the assumption is that experts will
provide causal models to a policymaker, who wants to combine (the
information in) these models to reach her decision. Bradley,
Dietrich, and List have provided arguably reasonable desiderata for
combining causal models, and showed that there is no way of combining
causal models so as to satisfy all their desiderata.   The hope is
that we can provide conditions under which models are compatible. The
general approach to combining experts' judgements would then be to
combine the experts' models when they are compatible, and if not, just
place a probability on each model being the right model, using
relatively standard techniques based on the perceived reliability of
the experts who proposed them. Intuitively, if the experts' models are
not compatible, then the experts are disagreeing, so we should not try
to combine their models; rather, we should just assign a likelihood to
each model being right. On the other hand, if the models are
compatible, then we should consider a model that takes into account
both experts information.

With regard to abstraction, suppose that an expert provides a detailed
causal model, involving many variables. Such a detailed model may be
far too complicated for a policymaker to understand and work
with. What the policymaker wants is a high-level "macro" model of the
situation. Such a high-level model can result from combining many
variables at the "micro" level into one "macro" variable. There have
been recent arguments made that such a high-level model actually can,
in a precise sense, provide more information than a detailed model. A
high-level model can also be helpful when it comes to deciding
appropriate interventions to perform. For example, by introducing a

new concept such as "soccer mom", we may be able to make more sense out of voting data, and think of more useful interventions that can be performed (e.g., run political ads to influence soccer moms). But what precisely does it mean that a high-level causal model is a faithful abstraction of a low-level model? Intuitively, this should mean that the high-level model captures all the information in the low-level model, at the level of variables used in the high-level model. I hope to make this notion precise, and come up with algorithms for testing if a high-level model is a faithful abstraction of a low-level model. In practice, we also will want a notion of approximate abstraction; that is, a high-level model may not exactly capture all the information in a low-level model, but it may come close. A good notion of approximation will let us quantify how far off one causal model is from another. This will enable us to quantify how much we lose by working with a simpler, high-level model.

Accomplishments: We have made significant progress on the goal of combining models. In a paper that appeared in AAAI 2018, Dalal Alrajeh, Hana Chockler, and I provided an approach for doing just what was hoped for in the proposal: we defined a notion of compatibility for causal models, and showed how compatible causal models can be combined.   In recent follow-on work with my Ph.D. student Meir Friedenberg, which will KR 2018, we showed how causal models can be combined in cases where the experts might disagree on the causal structure for variables that appear in both models due to having different focus areas. We provided a new formal definition of compatibility of models in this setting and show how compatible models can be combined.

With regard to abstraction, I am working actively with Sander Becker (Utrecht) on Frederick Eberhardt (Cal Tech) on finding good notions of abstraction and approximate abstraction.

Training Opportunities: Nothing to Report

Results Dissemination: The results of this project have been presented at AAAI (a major AI conference) and at numerous invited talks given by the PI.

Honors and Awards: Recipient of Lady Davis Fellowship, Hebrew University, 2018.

Elected Chair-Elect of the Section on Information, Computing, & Communication of AAAS (American Association for the Advancement of Science): term of office 2018-2021

Jin Yuelin Lecturer at Tsinghua University, 2017.

Selected Fellow of the Game Theory Society, 2017.

Protocol Activity Status:

Technology Transfer: Nothing to Report

 PARTICIPANTS:

 Participant Type: Faculty
 Participant: Joseph Halpern
 Person Months Worked: 3.00   **Funding Support:**
 Project Contribution:

International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Matvey Soloviev
Person Months Worked: 2.00   **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Meir Friendenberg
Person Months Worked: 1.00   **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Smaranda Sandu
Person Months Worked: 1.00   **Funding Support:**
Project Contribution:
International Collaboration:
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National Academy Member: N
Other Collaborators:

ARTICLES:

RPPR Final Report
as of 20-Sep-2018

Publication Type: Journal Article   Peer Reviewed: Y   **Publication Status:** 1-Published
Journal: Topics inCognitive Science
Publication Identifier Type: Publication Identifier:
Volume: 6   Issue: 2   First Page #: 245
Date Submitted: Date Published:
Publication Location:
Article Title: Decision theory with resource-bounded agents
Authors:
Keywords: decision making, resource-bounded agents, computation

Abstract: There have been two major lines of research aimed at capturing resource-bounded players in game theory. The first, initiated by Rubinstein \citeyear{Rub85}, charges an agent for doing costly computation; the second, initiated by Neyman \citeyear{Ney85}, does not charge for computation, but limits the computation that agents can do, typically by modeling agents as finite automata. We review recent work on applying both approaches in the context of decision theory. For the first approach, we take the objects of choice in a decision %where players are charged for the ``complexity'' of the Turing machine and charge players for the ``complexity'' of the Turing machine chosen (e.g., its %joe6 %running time). We show how this approach can be used to explain running time). This approach can be used to explain well-known phenomena like \emph{first-impression-matters biases} (i.e., people tend to put more weight on evidence they hear early on) %joe6 and \emph{belief polarization} (two

Publication Type: Journal Article   Peer Reviewed: Y   **Publication Status:** 1-Published
Journal: Artificial Intelligence
Publication Identifier Type: Publication Identifier:
Volume: 209   Issue: 0   First Page #: 1
Date Submitted: Date Published:
Publication Location:
Article Title: A logic for reasoning about ambiguity
Authors:
Keywords: ambiguityy, agreement, semantics

Abstract: Standard models of multi-agent modal logic do not capture the fact that information is often \emph{ambiguous}, and may be interpreted in different ways by different agents. We propose a framework that can model this, and consider different semantics that capture different assumptions about the agents' beliefs regarding whether or not there is ambiguity. We examine the expressive power of logics of ambiguity compared to logics that cannot model ambiguity, with respect to the different semantics that we propose.

Publication Type: Journal Article   Peer Reviewed: N   **Publication Status:** 1-Published
Journal: British Journal for thePhilosophy of Science
Publication Identifier Type: Publication Identifier:
Volume: 0   Issue: 0   First Page #: 0
Date Submitted: Date Published:
Publication Location:
Article Title: Graded causation and defaults
Authors:
Keywords: causality, normality

Abstract: Recent work in psychology and experimental philosophy has shown that judgments of actual causation are often influenced by consideration of defaults, typicality, and normality. A number of philosophers and computer scientists have also suggested that an appeal to such factors can help deal with problems facing existing accounts of actual causation. This paper develops a flexible formal framework for incorporating defaults, typicality, and normality into an account of actual causation. The resulting account takes actual causation to be both graded and comparative. We then show how our account would handle a number of standard cases.

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Journal: Journal of Artificial Intelligence Research
Publication Identifier Type: Publication Identifier:
Volume: 49   Issue: 0   First Page #: 143
Date Submitted: Date Published:
Publication Location:
Article Title: A procedural characterization of solution concepts in games
Authors:
Keywords: solution concepts, knowledge-based programs
Abstract: We show how game-theoretic solution concepts such as Nash equilibrium, correlated equilibrium, rationalizability, and sequential equilibrium can be given a uniform definition in terms of a knowledge-based program with counterfactual semantics. In a precise sense, this program can be viewed as providing a procedural characterization of rationality
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Journal: Games and Economic Behavior
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Volume: 87   Issue: 0   First Page #: 0
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Article Title: Conditional belief types
Authors:
Keywords: type space, hypothetical knowledge, conditional probability, counterfactuals
Abstract: We study type spaces where a player's type at a state is a conditional probability on the space. We axiomatize these spaces using conditional belief operators, examining three additional axioms of increasing strength. First, introspection, which requires the agent to be unconditionally certain of her beliefs. Second, echo, according to which the unconditional beliefs implied by the condition must be held given the condition. Third, determination, which says that the conditional beliefs are the unconditional beliefs that are conditionally certain. Echo implies that conditioning on an event is the same as conditioning on the event being certain, which formalizes the standard informal interpretation of conditional probability. The game-theoretic application of our model, discussed within an example, sheds light on a number of issues in the analysis of extensive form games. Type spaces are closely related to the sphere models of counterfactual conditionals and to models of hypothetical kno
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BOOKS:

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Book Edition: Volume: Publication Year: 2016   Date Received: 21-Aug-2016
Publication Location:
Publisher: MIT Press
Book Title: Actual Causality
Authors: Joseph Y. Halpern
Editor:
Acknowledged Federal Support: Y

CONFERENCE PAPERS:

Publication Type: Conference Paper or Presentation   **Publication Status:** 1-Published
Conference Name: Fifteenth Conference on Theoretical Aspects of Rationality and Knowledge(TARK 2015)
Date Received: 21-Aug-2016   Conference Date: 04-Jun-2015   Date Published:
Conference Location: Pittsburgh, PA
Paper Title: Bayesian games with intentions
Authors: Adam Bjorndahl, Joseph Y. Halpern, Rafael Pass
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation   **Publication Status:** 1-Published
Conference Name: Fifteenth International Conference on Principles of Knowledge Representation and
Reasoning (KR 2016)
Date Received: 21-Aug-2016   Conference Date: 25-Apr-2016   Date Published: 25-Apr-2016
Conference Location: Cape Town, South Africa
Paper Title: Sequential equilibrium and imperfect recall
Authors: Joseph Y. Halpern, Rafael Pass
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation   **Publication Status:** 1-Published
Conference Name: 15th International Conference on Autonomous Agents and Multiagent Systems (AAMAS
2016)
Date Received: 21-Aug-2016   Conference Date: 08-May-2016   Date Published: 08-May-2016
Conference Location: Singapore
Paper Title: Decentralised Norm Monitoring in Open Multi-Agent Systems
Authors: Natasha Alechina, Joseph Y. Halpern, Ian A. Kash, Brian Logan
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation   **Publication Status:** 1-Published
Conference Name: 32nd Conference   on Uncertainty in AI (UAI 2016)
Date Received: 21-Aug-2016   Conference Date: 25-Jun-2016   Date Published: 25-Jun-2016
Conference Location: New York City, NY
Paper Title: MDPs with unawareness in robotics,
Authors: Nan Rong, Joseph Y. Halpern, Ashutosh Saxena
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Publication Type: Conference Paper or Presentation   **Publication Status:** 1-Published
Conference Name: 17th ACM Conference on Electronic Commerce
Date Received: 21-Aug-2016   Conference Date: 24-Jul-2016   Date Published: 24-Jul-2016
Conference Location: Maastricht, Netherlands
Paper Title: Computational Extensive-Form Games}
Authors: Joseph Y. Halpern, Rafael Pass, Lior Seeman
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Conference Name: 35th Annual ACM Symposium on Principles of Distributed Computing
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Conference Location: Chicago, IL
Paper Title: Rational consensus: Extended Abstract,
Authors: Joseph Y. Halpern, Xavier Vilaca
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Conference Name: Thirty-First AAAI Conference on Artificial Intelligence (AAAI-17)
Date Received: 29-May-2017   Conference Date: 06-Feb-2017   Date Published: 02-Feb-2017
Conference Location: San Francisco, CA
Paper Title: Incentivising monitoring in open normative systems
Authors: N. Alechina, J. Y. Halpern, I. Kash, B. Logan,
Acknowledged Federal Support: **Y**

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Conference Name: Sixteenth International Joint Conference on Autonomous Agents and Multiagent Systems (AAMAS 2017)
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Conference Location: Sao Paulo, Brazil
Paper Title: Causality, responsibility, and blame in team plans
Authors: N. Alechina, J. Y. Halpern, B. Logan,
Acknowledged Federal Support: **Y**

Nothing to report in the uploaded pdf (see accomplishments).